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COMPARISON OF TWO- AND FOUR-POLE VSD MOTORS UP TO 4000 RPM

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ABSTRACT

Electric motors were originally developed for Directly-on-Line (DOL) operation. The speed of a motor was determined by the number of poles. A two-pole motor was used to reach 3600 rpm with 60 Hz grid frequency, and the lower speeds were achieved by higher pole numbers. Later on, the frequency converters were introduced to offer variable speed operation with Alternating Current (AC) motors. This was realized by a frequency converter with rated output frequency around 60 Hz and a slightly modified DOL motor. Even today, this original approach has remained as predominant practice with electric drives. However, this is not necessarily the optimal solution for Variable Speed Drives (VSD).

One alternative solution for speed ranges of traditional two-pole motors is a four-pole motor. The larger number of poles is compensated by the higher supply frequency. Today, this two-times-higher frequency can be achieved by most Low-Voltage (LV) and increasingly by standard Medium-Voltage (MV) frequency converters.

The main aim of this tutorial is to compare the two- and four-pole motors in VSD applications up to 4000 rpm. The comparison starts by describing the characteristic features of these motors. After that, the pros and cons will be dissected based on the physical features and example motors. Finally, the pros and cons of the four-pole design are evaluated from the system point of view using the traditional two-pole concept as the reference.

The comparison indicates strongly that the four-pole motor concept is superior in VSD applications. The most remarkable advantages are obtained in large MV electric motors. Thus, the increased application of the four-pole concept seems to be dependent on the end-user approval and open-minded thinking by motor and converter manufacturers. In essence, this new optimum is based on a step-wise modification on both sides.

INTRODUCTION

Electric motors were originally developed for Direct-on-Line (DOL) operation. In the beginning, the speed of an induction or synchronous motor was determined by the number of poles. A two-pole motor was used to reach 3600 rpm with 60 Hz grid frequency. Lower speeds were achieved by higher pole numbers, such as 1800 rpm (four poles), 1200 rpm (six poles), 900 rpm (eight poles) etc. Sometimes, there was a need to adjust the speed according to process requirements or energy savings. This need was originally solved by Direct Current (DC) motors. These commonly used motors possess superior controllability of speed and torque. Today, the same performance can be obtained by frequency converters with more reliable and economical Alternating Current (AC) motors. In principle, the same DOL motors can be used together with frequency converters to establish Variable Speed Drive (VSD).

Even today, most of the motors used together with frequency converters are only slightly modified DOL motors. The minor modifications are caused by the different requirements for the insulation, starting torque and cooling arrangement. Significantly, the rated supply frequency of VSD motors has been systematically close to 60 Hz. However, this is not necessarily needed. On the contrary, any speed range of a motor can be produced by several combinations of the pole number and supply frequency range. Particularly, the speed range around and above 3600 rpm, covered traditionally by two-pole motors, can be generated by a four-pole motor and a frequency converter with higher supply frequency.

The main aim of this tutorial is to compare the two-pole and four-pole motors in VSD applications. This comparison is motivated by the fundamental idea to replace the two-pole motors by four-pole motors in most of the VSD applications. In this paper, these traditional two-pole applications are referred shortly as high-speed VSD applications.

The tutorial starts by presenting the characteristic rotordynamic and vibration behavior of two-pole electric motors. This background, particularly including the description of twice-line-vibrations, is needed for the well-founded comparison. This prelude is followed by the discussion of the main structural differences of the two- and four-pole motors. After this, the performance and other characteristics of these motors are compared in traditional two-pole VSD applications. Finally, the pros and cons of different pole-number solutions are discussed from more general system point of view before the concluding remarks.

VIBRATIONS OF TWO-POLE MOTORS

Two-pole motors are industrial workhorses used as high-speed, prime movers. High speed for these motors means high unbalance excitation forces which are proportional to the second power of rotational speed. Thus, it is natural that the control of vibrations and rotordynamics plays a vital role in the design of these motors. Next, the characteristic features of two-pole motor vibrations are explained.

Critical Speeds

Lateral critical speed is defined as a shaft rotational speed at which the rotor-bearing-support system is in a state of resonance (API 684 2005). Operational speed(s) must be separated from the critical speeds by a separation margin. These margins are defined by international standards like IEC, by industrial standards like API, or by internal standards of a manufacturer. A typical value for the separation margin of electric motors is 15 % (API 541 2014, API 546 2008).

Usually, the most concerning resonances, in this context, are related to the flexural modes of the rotor. A natural choice is to design a rotor with subcritical operation. This means that the lowest flexural critical speed is above the maximum operational speed. Almost all of the multi-pole ($p \geq 4$) motors and motors equipped with antifriction bearings are designed for subcritical operation. Figure 1 shows as an example the vibrations of a 3000 HP (2.25 MW), two-pole, 50 Hz, rib-cooled, induction motor with antifriction bearings during a slow run-up with full magnetic flux. The blue curve gives the direct value of vibrations including all the components and the red curve the once-per-revolution (1X) component. The lowest rotor flexural critical speed occurs at 3770 rpm. Thus, the separation margin of rotational speed 3000 rpm to this mode is about 26 %. Actually, the rotational speed of this motor, and all induction motors, is slightly below the synchronous speed due to the slip (Fitzgerald, et al. 2003). In this tutorial, the synchronous speed, obtained by dividing the supply frequency by the number of poles and multiplying this product by 120, is systematically used to define the rotor speed.

Figure 1 shows that there are some other resonances below the operating speed, but they are not excited by the 1X excitation. These resonances will be discussed later.

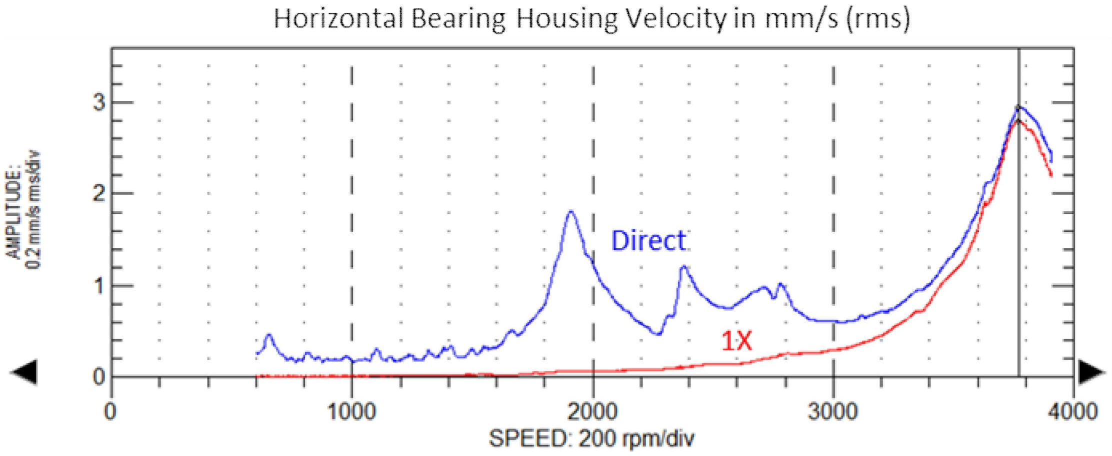


Figure 1: Bearing Housing Vibrations of a Two-Pole 3000 HP Induction Motor with Antifriction Bearings.

Small two-pole motors with journal bearings operate usually below the first critical speed. However, the subcritical operation is not practical with higher power ratings. With DOL motors, the dividing power is around 2000 HP (1.5 MW) depending on the motor type. Above this dividing power, it is reasonable to use the super-critical rotor design for constant speed motors.

As an example, Figure 2 shows the vibrations of a 6000 HP (4.5 MW), two-pole, 60 Hz, motor with sleeve bearings during a slow run-up with full magnetic flux. As can be seen, the 1X component dominates and two resonance peaks can be observed: the lower peak (2080 rpm) is the horizontal rotor mode and the higher peak (2610 rpm) the vertical mode. In electric motors, it is typical that the horizontal and vertical critical speeds are separated due to differences in oil film and support stiffness in these directions. Very often, the horizontal critical speed is so well-damped that for the observer there seems to be only one critical speed. In this case, the operating speed 3600 rpm is far away from the resonance peaks and the separation margin is 27 %. The design is perfect for a DOL motor.

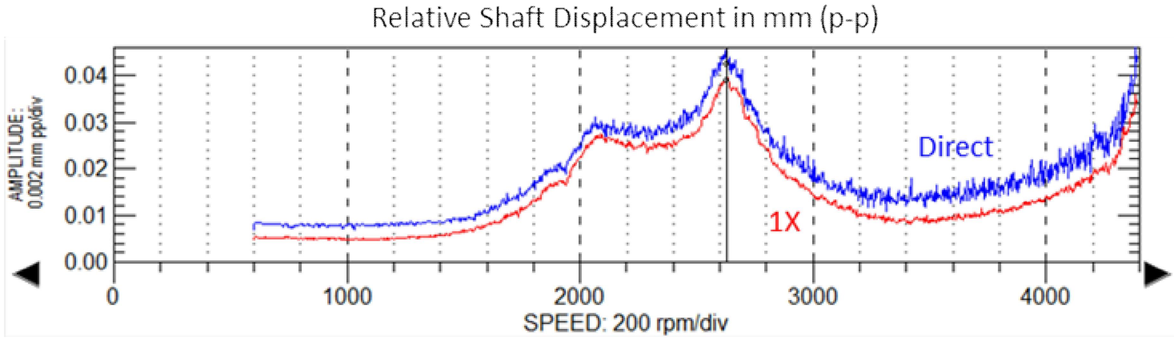


Figure 2: Shaft Vibrations of a Two-Pole 6000 HP Induction Motor with Sleeve Bearings.

Sub- and Super-Critical Rotor Designs

In general, it is better if the critical speeds are above the operating speed. The location of the first rotor critical speed is so important that motor designs are divided into two categories: sub-critical and super-critical design. In connection with electric machines these categories are often referred as rigid-shaft and flexible-shaft designs (Owen 1991). However, in this tutorial, the more common terms sub- and super-critical are systematically used. Figure 3 shows that, in super-critical machines, the critical speed is below and in sub-critical machines above the operating speed. A vast majority of all electric machines are realized by sub-critical design. In practice, all small motors and motors equipped with antifriction bearings are sub-critical machines. The super-critical design is used almost exclusively in large two-pole motors with sleeve bearings.

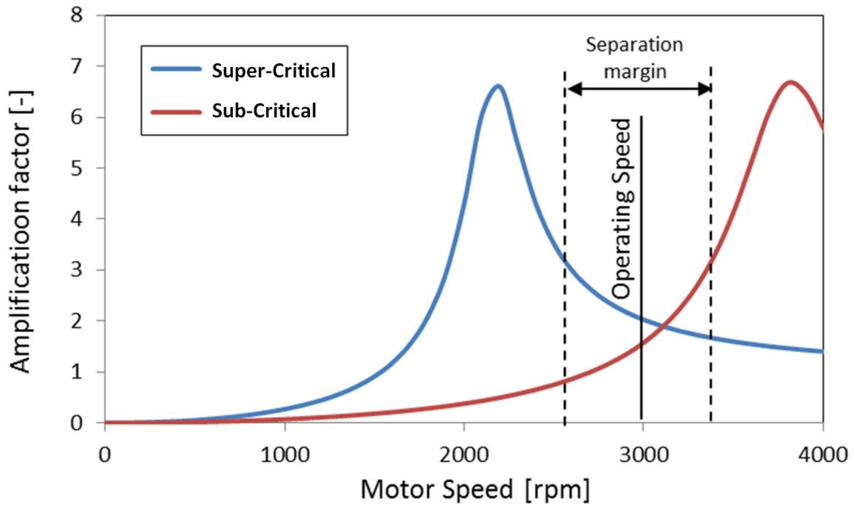


Figure 3: Super-Critical and Sub-Critical Design of DOL Electric Motors.

Twice-Supply-Frequency Excitations

Rotor critical speeds are an important part of any motor design. Another important design issue of two-pole DOL motors is the twice-line-frequency vibrations. These vibrations occur at 120 Hz when the line frequency is 60 Hz. In VSD motors, these vibrations occur on two times the supply frequency. Thus, in this tutorial, these are referred as the twice-supply-frequency (2F) vibrations.

The origin of these vibrations is the fundamental magnetic field (Finley et al., 2000). This field produces traction on the cylindrical surfaces of the rotor and stator. The tangential component of this traction is exploited for the torque production. Unfortunately, this tangential component cannot be generated in the air-gap without a substantial radial component. This radial component, in turn, does not produce torque but generates a mechanical pressure distribution. This pressure is proportional to the second power of the magnetic flux density. In two-pole motors, the main component of this rotating pressure field can be described as a sinusoidal distribution with two wavelengths in one circumference. Figure 4 shows this axially uniform pressure field of two-pole motors rotating with synchronous speed Ω_{syn}. This mechanical pressure field deforms the cylindrical stator into an elliptical shape that is also rotating with synchronous speed (Figure 4).

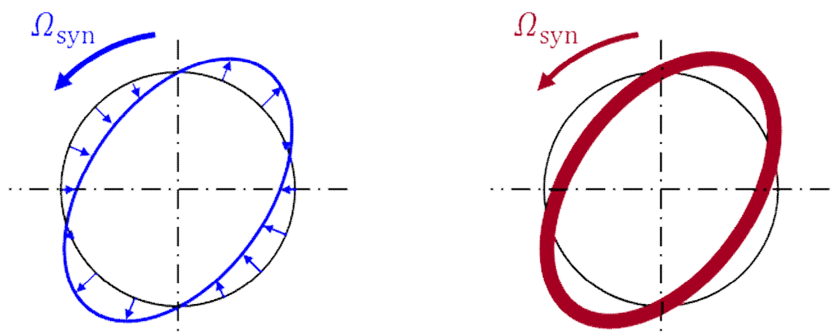


Figure 4: Rotating Pressure Field and Stator Deformation of Two-Pole Motors.

In principle, the amplitude of this fundamental field excitation is large, but the pressure distribution is internally balanced (Figure 4). The stiffness of the cylindrical stator yoke is much higher than the stiffness of a typical frame. Thus, the elliptical deformation of the stator core occurs without any significant resistance from the frame structures. However, this elliptical deformation is transmitted to the frame and other parts of the motor via the support structures of the stator as intermediate walls. Figure 5 shows schematically how the rotating pressure, deforming the stator in elliptical shape, excites the horizontal motor vibrations due to the intermediate walls and support asymmetry with respect to the horizontal middle plane.

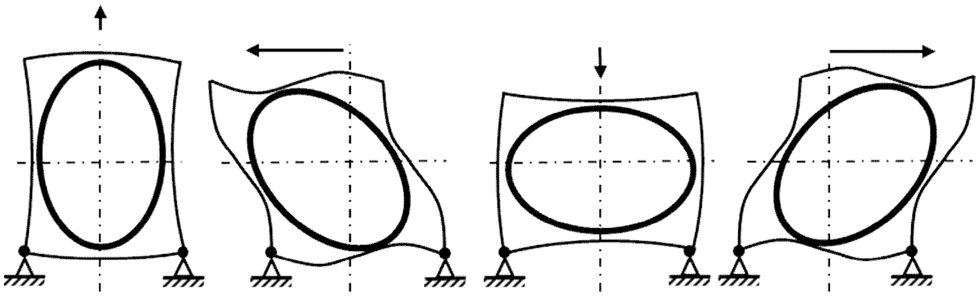


Figure 5: Schematic Excitation Mechanism of Rotating Elliptical Deformation in Two-Pole Motors (Holopainen et al., 2010).

In two-pole motors, the 2F vibrations of end windings are excited either mechanically by the rotating elliptical stator deformation or directly by the rotating magnetic field. In very large electric machines, the stator end windings must be equipped with a support structure to prevent excessive vibrations (IEC 60034-32, 2015).

The twice-supply-frequency (2F) response can be reduced a) by decreasing the magnetic field amplitude in the air-gap, b) by increasing the stator yoke thickness, or c) by isolating mechanically the stator from the motor frame (Finley et al., 2000). The first one reduces the excitation amplitude, the second one reduces the stator deformation, and the third one reduces the structural-born propagation of vibrations. All of these approaches are exploited to limit the 2F vibrations. The control of 2F vibrations is an integral part of the design of all large two-pole motors.

The twice-line vibration is a well-known feature of two-pole electric machines. This feature turns up also in the standards. For example, the international IEC 60034-14 (2003) standard allows for Grade A motors larger vibration levels, i.e. 2.8 mm/s instead of 2.3 mm/s (rms), if the dominating source is twice-line frequency. On the contrary, there is even a company standard requiring that the twice-line component is less than 1.4 mm/s (rms) when the general requirement is 2.3 mm/s (rms).

Figure 6 shows as an example the vibrations of a 3000 HP (2.25 MW), two-pole, 50 Hz, rib-cooled, induction motor with anti-friction bearings during a slow run-up with full magnetic flux. The direct and 1X components of this same test run were shown in Figure 1. In two-pole motors, the 2F component is the same (if the slip is disregarded) as the twice per revolution component, i.e., 2X. Figure 6 shows that there are two resonances excited by the 2F excitation. The lower one (1900 rpm) is the first horizontal mode with the rotor and stator in the same phase, and the upper one (2370 rpm) is the second horizontal mode with the rotor and stator in the opposite phase. Thus, the resonances below the operating speed of Figure 1 are explained.

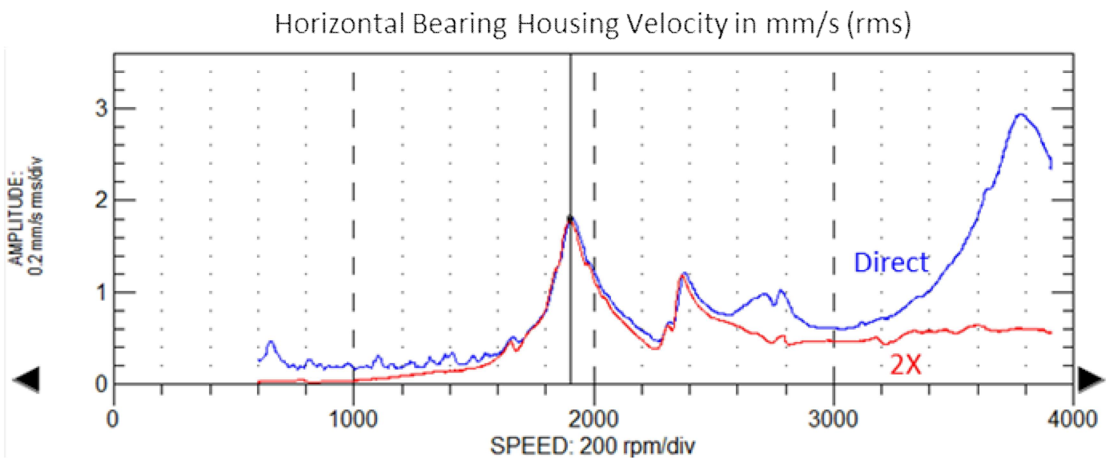


Figure 6: Bearing Housing Vibrations of a Two-Pole 3000 HP Induction Motor with Antifriction Bearings.

In two-pole electric motors, the weight of the stator is much larger than that of the rotor. Thus, the critical speeds are determined, not only by the rotor-bearing-support system, but also by the massive stator with its support system. Usually, the lowest natural modes of a motor can be described by defining the predominant motion of the rotor and stator masses. The lowest mode is typically characterized by the horizontal motion of the rotor and stator in the same phase. The second horizontal mode is on a somewhat higher frequency with the rotor and stator motion in the opposite phase. The similar behavior prevails with the vertical modes. In principle, there are two horizontal and two vertical natural modes and frequencies corresponding to the first rotor bending mode. However, the sensitivity of these modes on critical speeds varies depending on the excitation type (1X or 2F), modal shapes and bearing damping.

Actually, the natural mode excited by the critical speed (3770 rpm) of Figure 1 is the same as the mode behind the lower resonance (1900 rpm) of Figure 6. The frequency of this first horizontal mode is 63 Hz. The frequency of the second horizontal mode is 79 Hz. The observed behavior can be presented with a Campbell diagram. Figure 7 shows schematically the behavior observed in Figure 1 and Figure 6. As can be seen there are two critical speeds below the operating speed. At least one of these resonances is inherently present in large electric motors with antifriction bearings. In order to avoid this, the natural frequency of the first horizontal mode would have to be above 120 Hz, which is unreasonable.

It can be mentioned that there are certainly other natural frequencies between 60 Hz and 120 Hz. For example, the first vertical mode is slightly above the first horizontal mode. However, the twice-supple-frequency seems to excite the horizontal modes more easily due to the asymmetry of the stator supporting structure (Figure 5).

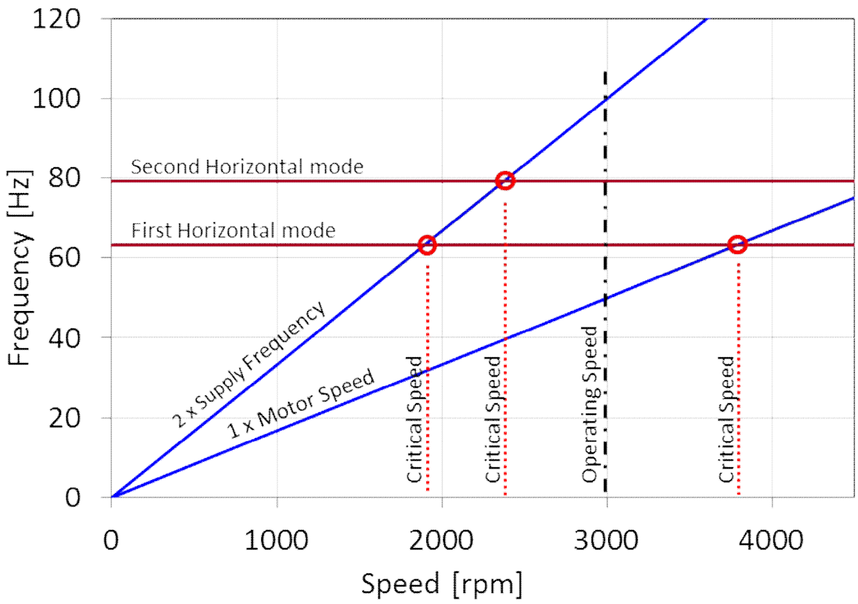


Figure 7: Campbell Diagram of a 3000 HP (2.25 MW) Two-Pole Motor Showing the Critical Speeds Excited by the 1X and 2F Excitations.

ALTERNATIVE CONCEPTS

If a two-pole motor is used in a VSD application, the sub-critical design is clearly preferable because it provides an operating speed range without lower bound, i.e., from the minimum speed of the bearings to the maximum speed of the motor. However, the sub-critical design may entail some sacrifices in electrical performance due to the rotordynamic requirements. In addition, there is a physical power-speed limit for the reasonable sub-critical designs. This limit is around 6700 HP (5 MW) when we have a 3600 rpm motor. Even if the sub-critical two-pole design is used, the 2F excitations are always present and they may excite resonance vibrations below the operating speed range. This can be prevented, but again, the reduction of 2F vibrations may require sacrifices of electrical performance or robust design.

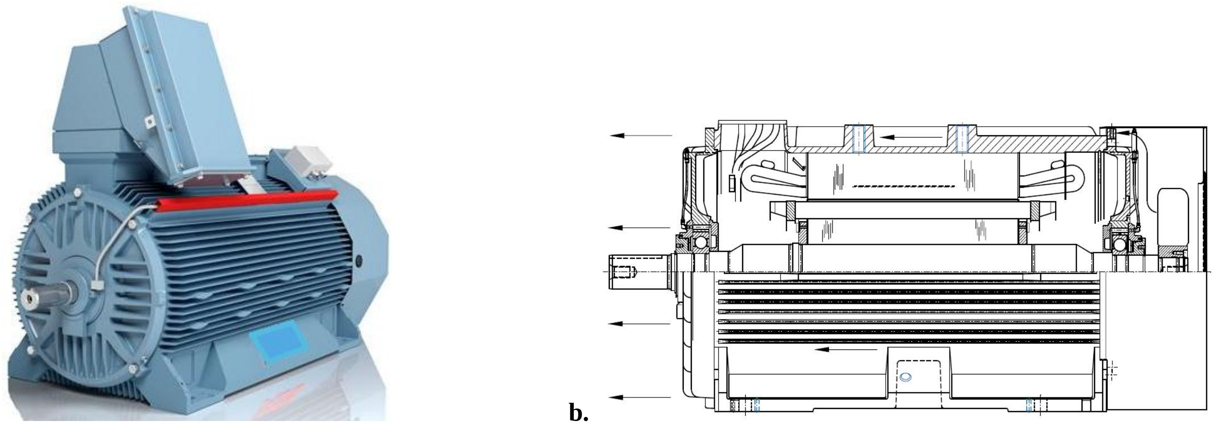
It seems to be clear that in many VSD applications a two-pole motor is not an optimal solution. The situation is not good, but what could be an alternative? An attractive solution for this challenge is an old but rarely used concept: a four-pole motor with twice as high supply frequency and sub-critical rotor design. In the next section, the main physical features of two-pole and four-pole motors are discussed in order to understand the background of the reasoning.

DIFFERENCES OF TWO- AND FOUR-POLE MOTORS

This Section is devoted to the main differences between the two- and four-pole motors. This discussion is focused on the differences connecting the electric, thermal and mechanical design together. However, the Section is started by presenting the main motor types. In general, this tutorial covers both of these motor types.

Typical Motor Types

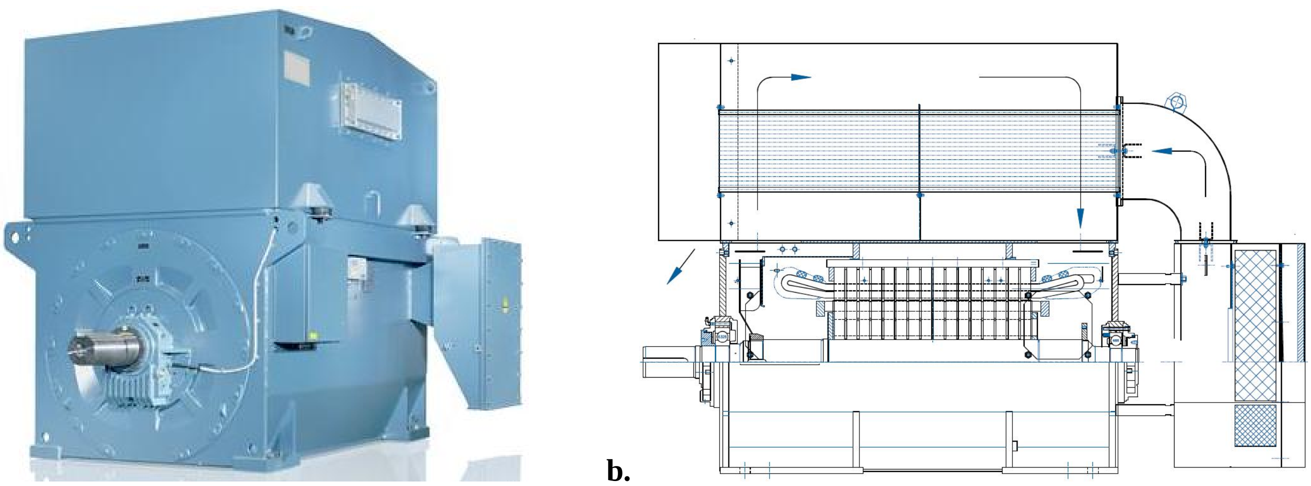
Small electric motors consist of cast frame and shields with antifriction bearings. The cooling is arranged by conducting the heat radially through the stator yoke to the frame ribs, and further, by convection induced by the axial air flow. Figure 8a shows a rib-cooled induction motor with antifriction bearings. Figure 8b shows the longitudinal cross-section and typical cooling arrangement.



a. b.

Figure 8: a) Rib-Cooled Induction Motor with Antifriction Bearings, b) Typical Cross-Section of a Totally Enclosed Fan Cooled (TEFC) Motor.

Motors with higher power rating require better heat transfer. Figure 9a shows an example of a modular induction motor with journal bearings and an air-to-water heat exchanger. Figure 9b shows a typical cross section and cooling arrangement with an air-to-air heat exchanger. In general, there are several alternatives for the primary and secondary cooling circuits. Basically, the primary circuit



a. b.

Figure 9: a) Modular Induction Motor with Journal Bearings and Heat Exchanger, b) Typical Cross-Section of a Totally Enclosed Air to Air Cooled (TEAAC) Motor.

flows through the electrically active parts and the heat exchanger. The secondary cooling circuit transfers the heat forward. In this context, the primary circuit is more important. The air flows through the stator and rotor core via the axial and radial air ducts. In multipole ($p \geq 4$) motors, the pressure difference needed for the primary circuit is produced by one or two impellers mounted on the shaft (see Figure 9b). In two-pole motors, due to the higher speed, the necessary pressure difference can be obtained by radial air-ducts of the rotor core without any additional shaft mounted impellers.

Cross-Section and Flux-Flow Pattern

Figure 10 shows the cross-section of electromagnetically active parts of a typical two-pole (~ 6000 HP) and a typical four-pole (~3000 HP) motor together with magnetic flux lines. Both of the cross-sections are qualitatively similar. The differences are concealed in the relative dimensions. The outer diameter is determined by the frame size and it is usually equal for all pole-numbers.

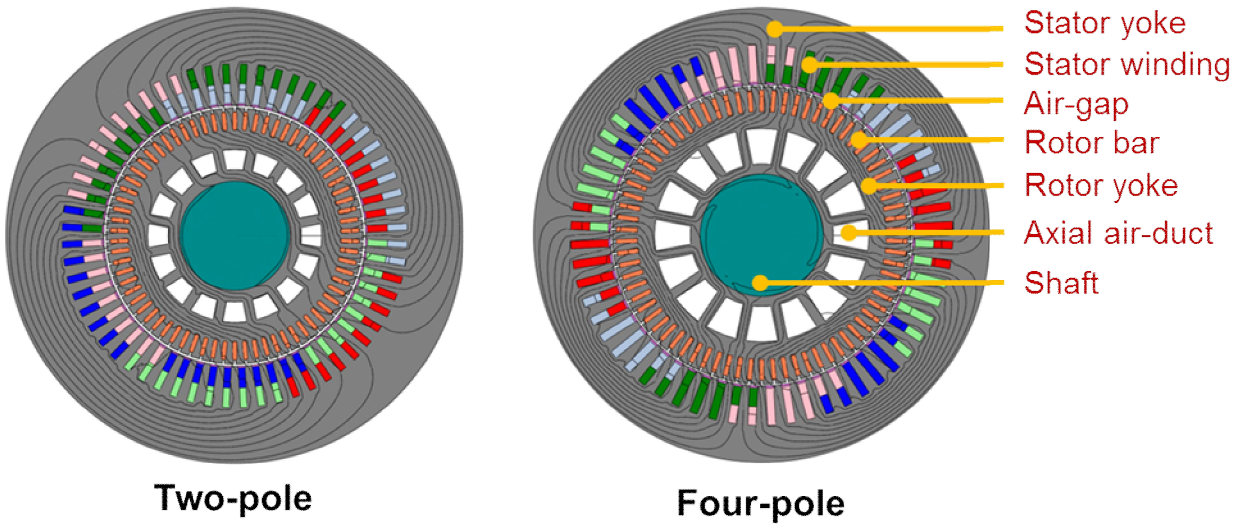


Figure 10: Flux-Flow Patterns of a Two-Pole and a Four-Pole Motor (Not in Same Scale).

First, it can be seen that the pole-number determines the path of the magnetic flux. Because the magnetic flux density is limited by the saturation of magnetic materials, the flux density maximum in the stator yoke of both cross-sections is roughly equal. This means that the stator-yoke thickness of the two-pole motor is about twice as large as the thickness of the four-pole motor. Because the radial space required for the stator teeth and winding region is about the same, the air-gap diameter of the four-pole motor can be increased and is usually larger than that of the two-pole motor.

The radial space needed for the rotor teeth and bars is again about the same in both cross-sections. The fundamental flux must flow through the cage bars, along the rotor yoke and inner ring one pole-pitch-length, and back again through the bars. Thus, there is again a need for roughly twice as large radial space in two-pole motors than in four-pole motors. This need is balanced with the requirement of axial cooling air flow, which manifests itself in the axial cooling ducts. Finally, the diameter of the shaft defines the bending stiffness of the rotor with a minor contribution of the core laminations.

Axial air-ducts shown in Figure 10 are needed in medium and large power electric motors. The cooling air flows in these ducts through the rotor core or into the radial air-ducts as in Figure 9b. Small motors do not require axial ducts, and thus, whole the rotor cross-section can be used to fulfill the electromagnetic and mechanical requirements.

The description of the cross-sections can be finished by stating that the radial space is allocated to fulfill the electromagnetic, cooling and mechanical requirements. A balanced solution between these requirements is clearly different in a two-pole motor compared to a four-pole motor.

Stator and Rotor Windings

Figure 11 shows the end windings of a typical two-pole and a four-pole motor from the axial direction. The end windings are necessary to return the currents to the core. In an optimal case, the stator core currents produce a sinusoidal magnetic field in the air-gap. This can be approached by using optimal coil pitch which is dependent on the pole-number. The optimal coil pitch means that the magnetic field in the air-gap approaches a sinusoidal distribution yielding lower losses and torque ripple.

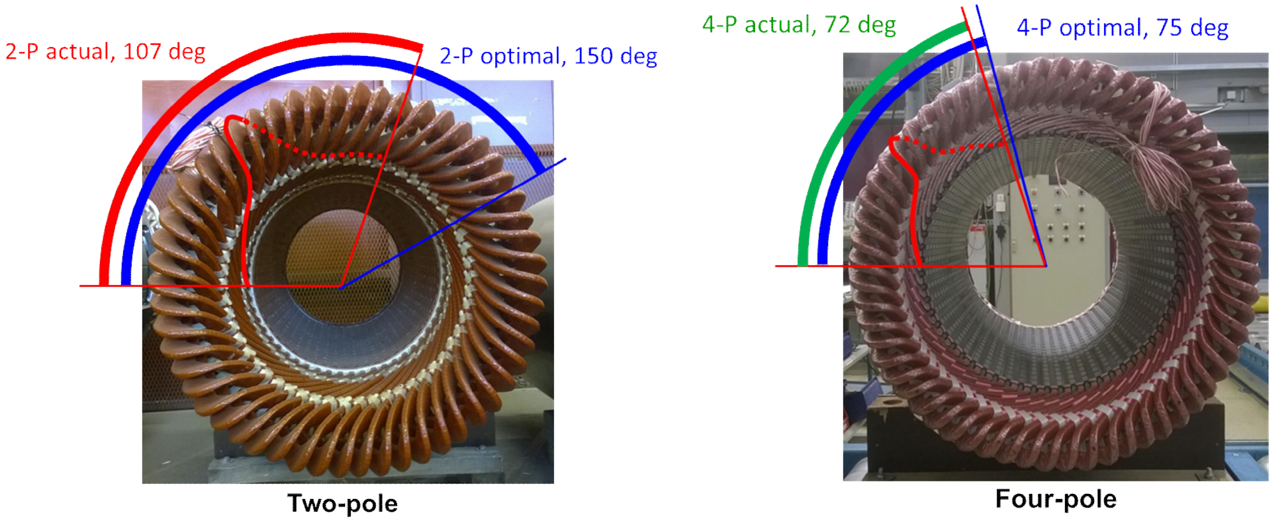


Figure 11: Winding-Ends of a Two-Pole and a Four-Pole Motor.

The optimal coil pitch of a two-pole motor would be 150 degrees, but due to the manufacturing requirements the actual pitch is always smaller and in this example case 107 degrees. In the contrary, the optimal coil pitch of a four-pole motor is 75 degrees and this can be easily achieved in the manufacturing. In practice, the number of stator slots determines an angle close to the optimal. In the example case of Figure 11 the number of slots is 60 and thus the actual angle 72 degrees.

Only the stator currents in the core region produce the magnetic flux for electromechanical conversion. The end windings are necessary, but they do not directly produce active power. Due to the resistive losses, there is a need to minimize the length of the end winding outside of the core. Figure 11 shows that the winding ends of the two-pole motor are longer than those of the four-pole motor. Thus, it means, in general, that the resistive losses in the winding ends are smaller in the four-pole design.

Longitudinal Layout

Figure 12 shows the longitudinal cross-section of a typical two-pole and a four-pole motor. The supply voltage of the motors is equal.

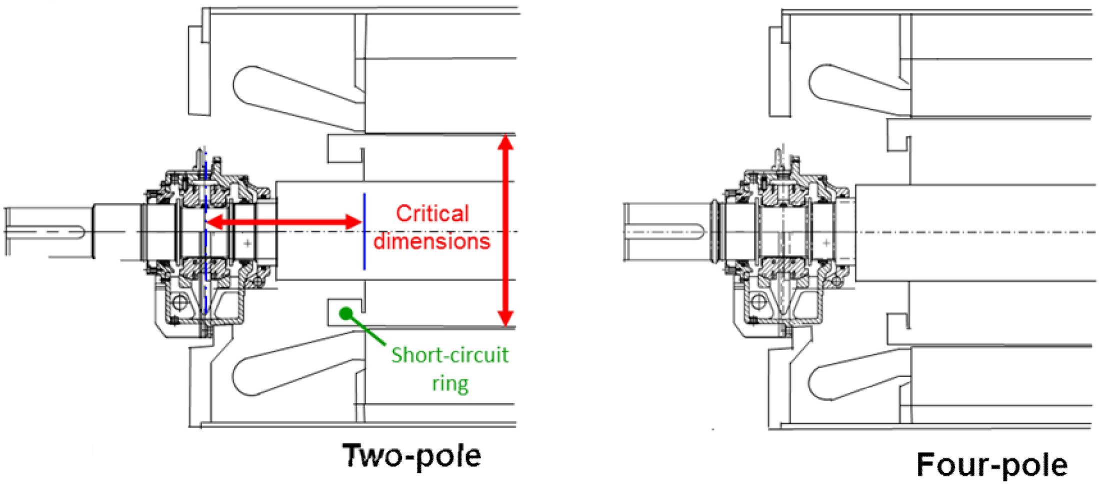


Figure 12: Longitudinal Cross-Sections of a Two-Pole and a Four-Pole Motor.

The actual coil pitch discussed above can be seen also in the axial length of the coil ends. The four-pole motor has clearly shorter axial coil ends. This means that the core of a four-pole motor can be longer in proportion to the frame length and the bearing span.

Another difference follows from the air-gap diameter. Because the air-gap diameter of the four-pole motor can be larger, there is more space inside the coil ends to be used for the bearing and sealing arrangement. This means that the bearing span can be decreased with respect to the core length.

A third difference can be seen indirectly. The short-circuit ring of the two-pole motor is larger than that of the four-pole motor. The cross-section area is roughly twice as large reflecting the twice as long current path in the two-pole motor. As with the stator winding end currents, these cage winding currents in the end section do not directly produce active power. In addition, the smaller weight of the four-pole short-circuit ring is advantageous from the rotordynamics point of view.

COMPARISON OF TWO- AND FOUR-POLE VFD-MOTORS

Comparison Background

One way to evaluate the two-pole and four-pole motors in VSD applications is to compare alternative designs. Next, a two-pole standard 6 kV motor is compared to a slightly modified standard four-pole motor. Both of these motors are originally design for direct-on-line operation with supply frequency 50 Hz. The rated power of the two-pole motor is 10000 HP (7.5 MW). The converter supply changes the design slightly, but the effects are roughly similar for both motors. Thus, the alternatives for 10000HP@3000rpm are:

- A two-pole DOL motor with 50 Hz supply
- A four-pole DOL motor with 100 Hz supply

The frame-size of the two-pole motor is 630 (= shaft height 630 mm) and of the four-pole motor, one smaller, 560. A standard four-pole 50 Hz motor with 3 kV supply voltage was chosen for comparison because the voltage will be doubled with double supply frequency. The insulation class of this four-pole motor was increased accordingly, because it has an effect on convection. In addition, the internal fan of this four-pole motor was removed because the radial air-ducts of the rotor with higher speed produce a pressure difference needed to circulate the cooling air. However, this additional axial space (200 mm) of the removed fan was not used for the increase of the core length. Finally, the original shaft diameter was used, and thus, both of the rotors were super critical.

The comparison is made for the following topics:
- Power per weight
- Cooling capacity
- Maximum speed with sub-critical rotor design
- Twice-supply-frequency vibrations
- Rotor thermal stability
- Total losses
- Separation margin against short circuit loads
- Converter availability
- Motor controllability
- Interchangeability
- Power supply cables

Power per Weight

There is a simple equation for the mechanical power P_{mec} of an electric motor (Pyrhönen et al., 2008):

$$P_{\text{mec}} = C_{\text{mec}} \cdot D^2 \cdot L \cdot n_{\text{syn}} \tag{1}$$

where D is the air-gap diameter, L is the (equivalent) core length, n_{syn} is the synchronous speed, and C_{mec} the machine constant. Without going into the details, Equation (1) means roughly that, if the speed of the rotor and the magnetic flux density amplitude in the air-gap are equal, the mechanical power is determined by the rotor core length and the diameter. Thus, the power is proportional to the volume of the rotor core. Figure 13 shows the cross-sections of the example motors in the same scale. In this case, the air-gap diameter of the four-pole rotor is even 3 percent larger than that of the two-pole rotor regardless of the frame size. The smaller (and shorter) frame and the inner fan of the standard design yields an 11 percent shorter core length for the four-pole motor. However, the rotor core volumes are practically equal. This means roughly that the same power can be produced by a one frame-size smaller motor, if four-pole design is applied. The power per weight ratio will be discussed later and a rough estimate will be given.

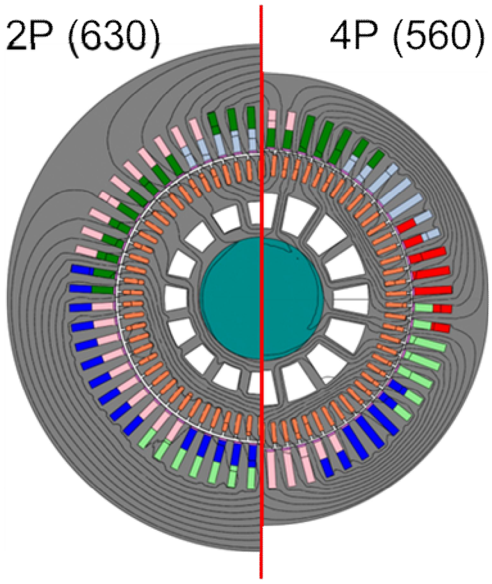


Figure 13: Cross-Sections of a Two-Pole and a Four-Pole Motor in the Same Scale.

Maximum Speed with Sub-Critical Rotor Design

It is not meaningful to compare the maximum speed without considering simultaneously the critical speeds. With VSD applications, the reasonable power-speed limit with sub-critical design is probably the most interesting feature related to the maximum speed. As stated above, this limit is about 6700 HP (5 MW) at 3600 rpm depending on the motor type. With lower speeds, the power limit is higher and for higher speeds, the power limit is lower. Qualitatively, it is evident that the four-pole design yields higher limit. There are several contributing features for this in four-pole motors. First, the active parts of a standard four-pole motor produce roughly the same power as a one-frame-size larger two-pole motor. Second, a smaller frame size means that the bearing span is shorter and the critical speeds with a same shaft diameter higher than the critical speeds with a larger frame size. Third, the four-pole rotor design has more radial space available for a thicker shaft, and thus, for higher critical speeds (Figure 11). Fourth, the axial distance between the core and the bearing center plane of a four-pole motor can be made much smaller for a four-pole motor than for a two-pole motor (Figure 10). All of these contributing factors together indicate strongly that the power-speed envelope of four-pole sub-critical motors is much higher than that of two-pole motors. As an example, a calculation example shows that a 9400 HP (7.0 MW) sub-critical motor with maximum speed 3750 rpm can be realized using the four-pole concept and conventional technology.

Twice-Supply-Frequency Vibrations

The twice supply-frequency excitations occur in all electric motors. However, the resulting vibrations are mainly known from the two-pole motors. Because the flux density amplitudes are usually slightly higher in multi-pole ($p \geq 4$) motors, the explanation must be somewhere else. The natural frequencies of these symmetric stator modes are several hundreds of Hertz. Thus, the effect of inertia forces is minor and the stator deformations due to the rotating pressure field are basically quasi-static. Actually, the explanation for the over-representation of two-pole motors in excessive 2F vibration cases is based on the pressure distribution and the corresponding deformation.

Figure 14 shows schematically the difference of the two-pole and four-pole stator deformations. It is evident that the two-pole distribution generates distinctly larger deformation than the four-pole distribution, if the stators and flux densities are equal. In practice, the stator yoke thickness is smaller and the flux density even higher in four-pole motors. However, in practice, the quasi-static deformations of four-pole and other multi-pole motors are smaller than in two-pole motors. It can be added, that the dynamic effects in this simplified analysis are neglected because the natural frequencies of these modes are much higher than the excitation frequencies. Finally, it can be added that in four-pole motors the twice-supply-frequency (2F) is equal to four-times the synchronous rotational frequency, i.e. in four-pole motors 2F ≈ 4X.

In summary, two-pole motors are prone to the twice supply-frequency vibrations due to the inherent characteristics of the loading and structural arrangements. The inherent characteristics of four-pole motors are more appropriate to limit the harmful effects of these vibrations.

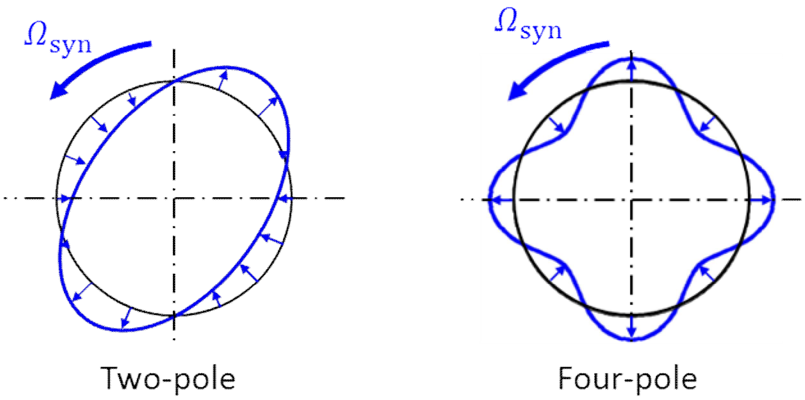


Figure 14: Rotating Pressure and Deformation Shape of a Two-Pole and a Four-Pole Stator due to 2F Excitation.

Rotor Thermal Stability

The rotor thermal bow is a remarkable nuisance particularly in flexible shaft two-pole motors. The thermal bow is generated either by the asymmetric temperature distribution of the rotor or by the asymmetric structural behavior of the rotor. In both cases, the shaft under the core can be assumed to be the homogeneous part and the core the source of asymmetric behavior. A rough estimate of the sensitivity S for thermal bow can be determined by the ratio between the rotor core diameter, D_{core}, and shaft diameter, D_{shaft}.

$$S = \left(\frac{D_{\mathrm{core}}}{D_{\mathrm{shaft}}}\right)^4 \qquad (2)$$

The fourth power follows from the second moment of area formula describing the stiffness of a cross-section. It is obvious that by increasing the shaft diameter the stability can be improved. In four-pole motors, there is additional space available in the rotor core to increase the shaft diameter. In addition, the short bearing-span in proportion to the core length is advantageous to reduce the harmful effect of thermal bow. Thus, the four-pole rotor seems to be more appropriate to achieve a thermally stable rotor. However, this conclusion remains mainly qualitative, because the thermal bow, as a phenomenon, is highly statistical in nature and requires large number of manufactured rotors.

Total Losses

The total losses of the example motors were calculated. In order to get a fair comparison the mechanical losses (bearings and air friction) of both motors were assumed to be equal. It is well known that the eddy current losses are roughly proportional to the second power of supply frequency and the hysteresis losses are directly proportional to the supply frequency. Both of these loss components, comprising the iron losses, are expected to be much higher in the four-pole motor than in the two-pole motor. The resistive or copper losses are proportional to the resistance, i.e., the length and cross-section area of the conductors.

Table 1 shows the results. As can be seen, the iron losses of the four-pole motor are clearly higher due to the higher frequency. However, the decreased copper losses of the four-pole motor more than compensate the increased iron losses. The total losses of the four-pole motor are even 1 per-cent lower than those of the two-pole motor. The difference is not significant, but slightly surprising, because one of the main arguments against the four-pole design has been the increased iron losses. However, in this example case, the copper losses due to the longer current paths in the stator end windings and the rotor short-circuit rings equalize the total losses.

The power factor of the four-pole motor is slightly higher than that of the two-pole motor. This means that there is no need to increase the current rating of the frequency converter. In addition, if the rated switching frequency of the converter is high enough, the converter losses of two- and four-pole motors are roughly similar.

Table 1: Electrical Calculation Results of Two-Pole and Four-Pole Designs.

Parameter	Value		Unit
	630 2P	560 4P	
Supply voltage	6	6	kV
Power	10000	10000	HP
Frequency	50	100	Hz
Synchronous speed	3000	3000	rpm
Supply current	1.000	0.997	p.u.
Mechanical losses	1.000	1.000[1]	p.u.
Iron losses	1.000	1.766	p.u.
Stator copper losses	1.000	0.839	p.u.
Rotor copper losses	1.000	0.649	p.u.
Total losses	1.000	0.990	p.u.
Efficiency	1.000	1.000	p.u.
Power factor	1.000	1.003	p.u.

[1] The mechanical losses are set equal

Separation Margin against Short Circuit Loads

A short-circuit is the most common electric fault affecting the electric motor and rest of the drive-train (Holopainen et al., 2013). The situation is slightly different with VSD motors. A frequency converter isolates the motor from short-circuits occurring on the grid side of the converter. Thus, only short-circuits occurring in the power supply circuit between the motor and the converter must be considered with VSD drives. Further, since a short circuit is an unexpected phenomenon in the machine terminals, the converter control system cannot have any effect on the air gap torque during the transient.

There are several types of short-circuits: two-phase, three-phase and single-phase-to-ground faults. All of these occur as transient excitations including one or two of the following frequency components: supply-frequency (1F) and twice-supply-frequency (2F). The maximum air-gap torque of a two-phase-short-circuit is roughly ten times higher than the rated torque. However, the air-gap torque cannot be applied directly to the dimensioning of the drive-train components due to the distribution of inertia and dynamic effects (Holopainen 2015).

Figure 15 shows an example. The drive-train consists of two inertias: motor and impeller. The impeller inertia is 25 percent of the motor inertia. They are connected by a massless shaft. The torsional natural frequency of this system is 20 Hz and the damping ratio is 0.02. It is assumed that the motor operates in steady-state condition with rated power. The operating speed of the rotor, when a short circuit occurs, is given in the horizontal axis of Figure 15. The vertical axis shows the maximum torque of the shaft between the rotor core and impeller, i.e., in the coupling. The short circuit loading is taken from DIN 4024 (1988). The maximum momentary air-gap torque of this transient is 12.7 times the rated torque.

The physical behaviour behind the curves of Figure 15 may need additional explanation. Thus, for example, when the operating speed of a two-pole motor is 1200 rpm and a two-phase short-circuit occurs, the excitation frequencies are 20 and 40 Hz (= 1200 cpm and 2400 cpm). Further, the excitation frequencies of a four-pole motor in the same situation are 40 Hz and 80 Hz (= 2400 cpm and 4800 cpm). Thus, it seems to be clear that the four-pole design enables larger operational speed range with smaller amplification factors against the short circuit loads.

Converter Availability

The four-pole design means that the motor power supply frequency must be two-times higher in order to fulfill the requirement of four-pole design. Usually, low voltage (LV) frequency converters are capable to several hundred Hertz output frequency without derating and therefore those can be directly used with the four-pole design. On the contrary, the output frequency of medium voltage (MV) frequency converters used to be lower in the past. This means that newer designs of MV converters are directly feasible, while some older technologies (e.g. load commutated inverters, LCI) must be de-rated in order to reach higher output frequencies. In general, voltage source inverter based MV converters can directly be used for four-pole designs.

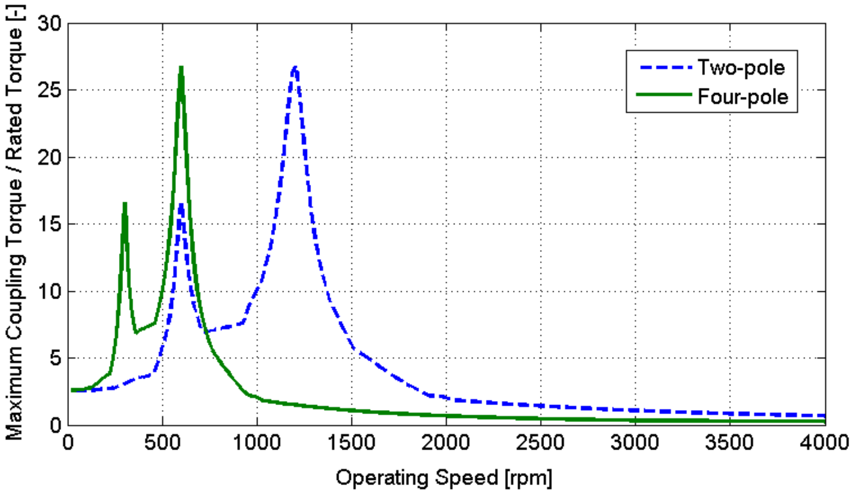


Figure 15: Amplification Factor between the Coupling and Air-Gap Torques for a Two-Inertia System with the Natural Frequency at 20 Hz.

Motor Controllability

Because of the high switching frequency and the fast control loops of the modern frequency converters, the number of machine poles is not a critical parameter, when the accuracy of the speed and torque control is considered. Thus, from the viewpoint of motor control, there are no major differences between the two- and four-pole designs. However, a higher stator-leakage inductance of four-pole machines reduces the current rise time and therefore slightly improves the control of these motors. With respect to torsional stability, and the potential closed-loop controller effects on torsional natural frequencies, it is important to recall, that those frequencies are not influenced by the pole-number and remain visible at the same frequency and with the same damping within both the torque and the speed control loop.

Interchangeability

Traditional VSD motors are very similar to DOL motors. Thus, in principle, there are two alternatives to supply a motor: directly from grid or via frequency converter. However, the designs of VSD and DOL motors have differentiated slightly even if the rated frequency is the same. Thus, this kind of interchangeability does not play such an important role, at least, with larger electric motors.

In some cases, the frequency converter is used to start the motor smoothly and the steady-state operation is carried out by supplying the motor direct on line. This eliminates the converter losses during the steady-state operation but limits the operation to a fixed predetermined speed. In addition, only one converter is needed for a set of motors. Thus, the starter applications are excluded from four-pole motors due to the double supply frequency.

Power Supply Cables

The electric resistance of a cable is dependent on the frequency. With increasing frequency, a so-called skin effect increases the effective resistance of cables. A four-pole motor has twice as high supply frequency compared to that of a two-pole motor. This means that there might be a need to increase the cross-section area of the cables between the four-pole motor and converter, particularly, if the distance is long. Typically, the cross-section area must be increased by 10 percent, to achieve the same load ability as in two pole motor case (IEC 60287-1-1, 2006). This may slightly increase the system cost of a four-pole motor compared to a two-pole motor.

EXPERIENCES OF FOUR-POLE DESIGN

The four-pole design has been used commonly for high-speed application with permanent magnet (PM) rotor constructions. The motivation for four-pole design has been the arrangement of magnets, which is unfavourable for two-pole design. The power range of these four-pole high-speed PM motors has been usually relatively small.

The design and testing of a large 60000 HP (45 MW) four-pole synchronous motor is presented in (Tessarola et al., 2011). This 3000 rpm VSD motor is supplied by four pulse-width modulation (PWM) multilevel voltage source inverters (VSI).

Smaller four-pole 120 Hz induction motors have been produced without any major issues. For example, three four-pole induction motors were delivered to be used as load motors on test floors. The rated power of these LV motors was 3750 – 4950 HP (2800 – 3680 kW) and speed range 500 – 3600 rpm. The motors were delivered 2006 – 2009. The first of these motors was tested more thoroughly. Figure 16 shows the shaft vibrations in non-drive end during the slow run-up with rated flux. As can be seen, the first vertical critical speed is above 4000 rpm and the first (well-damped) horizontal critical speed slightly below 4000 rpm. In this case, the twice-supply vibrations (2F) occur about four times the rotational frequency (4X). Unfortunately, this component was not recorded, and thus, it is not plotted on Figure 16. However, because the difference between the direct and 1X value is small and relatively constant, it is apparent that the twice-supply (or other) component do not excite the resonances of the structure. These three motors have served several years with wide speed range and with thousands of starts and stops. So far, the motors have served without interruptions or faults.

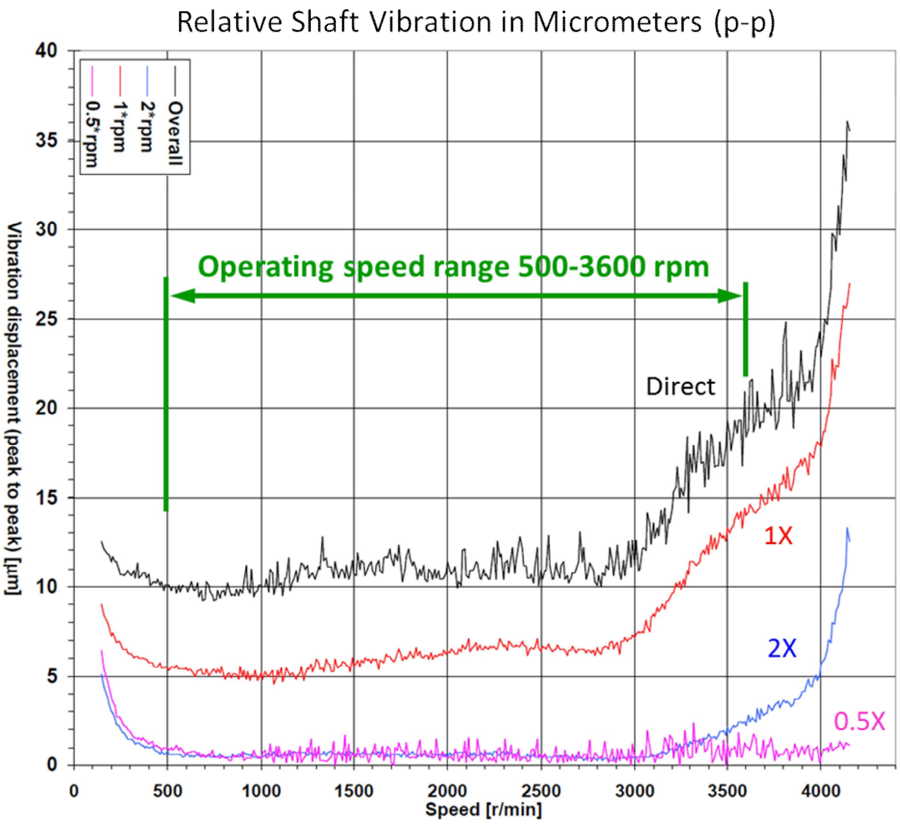


Figure 16: Shaft Vibrations of a Four-Pole 3750 HP Motor during Slow Run-Up.

In summary, the application of four-pole motors instead of traditional two-pole motors in VSD applications is not a new idea. There are four-pole motors running in daily service in different applications. The realization of existing four-pole drives has required mutual understanding of a motor supplier and a frequency converter supplier together with approval of a system integrator and an end user.

END USER BENEFITS AND DRAWBACKS

Most of the end users have practical experience of two-pole motors in practice. In this Section, the four-pole concept will be compared to this traditional alternative from the supposed end-user viewpoint.

More Power and Speed with Sub-Critical Design

The four-pole design enables to push the design speed-power limit upwards with sub-critical design. A rough estimate for a Totally Enclosed Water to Air Cooled (TEWAC) motor with maximum speed 3600 rpm is from 6700 HP (5 MW) with two-pole design to 9400 HP (7 MW) with four-pole design. The main contributing factors of four-pole design are a) the available radial space for thicker shaft below the rotor core, and b) the shorter bearing span with respect to the core length.

Smaller Foot Print

The four-pole design yields more power per frame size or motor weight. A rough estimate is that the same power can be produced by a one-IEC-frame-size smaller four-pole motor. The ratio of IEC frame sizes is about 1.122. The second power of this ratio can be used to get an estimate for the mounting area, i.e. -21 %, and the third power for an estimate of motor weight, i.e. -29 %.

Lower Vibrations

The four-pole design means lower vibrations due to two main contributing factors. First, the twice-line vibrations of four-pole motors are inherently much smaller than those of two-pole motors because the generalized stiffness of four-pole, i.e., cloverleaf shape is much higher than that of two-pole, i.e., elliptical shape. Second, the vibrations induced by the thermal bow are smaller due to the shorter relative bearing span and better thermal stability of the rotor. The better thermal stability can be achieved by using thicker shaft below the rotor core without any significant adverse effects on the electromagnetic or thermal performance.

Improved Safety Against Short-Circuit Loading

The four-pole design means that the short-circuit excitation frequencies, i.e. one- and two-times the supply frequencies, are two-times higher than those of the two-pole motors. Because one of the main design principles of torsional trains with electric drives is to adjust the first natural frequency below the lowest short-circuit frequency, the four-pole design gives more design space with larger operational speed range.

Increased Motor Reliability

The four-pole design means increased reliability due to lower vibrations and more robust motor construction. There are three contributing factors explaining the more robust construction. First, the winding ends are shorter, and thus, there is no need for support structures even in very large motors. Second, there is more radial space available in the rotor cross-section releasing the strict limitations of the shaft diameter and the cross-section area of cooling ducts. Third, there is no need to isolate mechanically the stator against the twice-line vibrations.

Lower Purchase Price

The four-pole design means lower purchase price. This follows from the manufacturing costs which are strongly related to the weight of the motor. Because the power-weight ratio of four-pole motors is higher than that of two-pole motors, the costs of four-pole motors are lower. In addition, the more robust design of four-pole motors decreases the relative manufacturing costs.

Lower Availability of Frequency Converters

The four-pole design means that the motor supply frequency must be two-times higher. Usually, low voltage (LV) frequency converters can be used for four-pole design directly. Also in medium voltage (MV) range, modern voltage source inverters can normally be used for four-pole design directly. Only in the very high power range >54000 HP (>40MW) where traditional LCI current source inverter technology is used, potential de-ratings may apply.

Not for Starter Applications

The four-pole design means that the starter applications are excluded. In these applications, the converter is used to start the motor smoothly and the steady-state operation is carried out by supplying the motor directly from grid like a DOL motor. This eliminates the converter losses during the steady-state operation, but limits the operation to a fixed predetermined speed.

Thicker Cables

The four-pole design means that the resistive losses in the cables between the motor and converter are higher. This can be compensated by larger diameter cables with a minor external cost.

CONCLUSIONS

This tutorial presented the four-pole concept for VSD applications up to 4000 rpm and above. The inherent differences between the two-pole and four-pole motors were described. Based on these physical features the performance of two- and four-pole motors was compared using two example motors. Finally, the end user advantages and drawbacks were discussed using the traditional two-pole motor as reference.

The presented material indicates strongly that the four-pole motor concept is superior in high-speed VSD applications. The increased application of four-pole concept is dependent on the approval of end users and open-minded thinking by motor and converter manufacturers. In essence, this new optimum is based on a step-wise modification on both sides.

The four-pole concept of this tutorial is based on the release of traditional connection between DOL and VSD motors. If this connection is removed and the feasible solution concurrently searched for the motor-converter combination, the optimal result might be a novel one. In this case, the four-pole concept seems to outperform the two-pole one in VSD applications. In general, there might be other similar motor-converter concepts expecting only to be discovered.

NOMENCLATURE

AC = Alternating current
API = American Petroleum Institute
DIN = Deutsches Institut für Normung (German Institute for Standardization)
DOL = Directly on line
IEC = International Electrotechnical Commission
LCI = Load commutated inverter
LV = Low voltage
MV = Medium voltage
P = Number of poles
PM = Permanent magnet
PWM = Pulse width modulation
TEAAC = Totally enclosed air to air cooled
TEFC = Totally enclosed fan cooled
TEWAC = Totally enclosed water to air cooled
VSD = Variable speed drive
VSI = Voltage source inverter
1X = Once per revolution
2F = Twice supply frequency
2X = Twice per revolution

REFERENCES

API 541, 2014, “Form-wound Squirrel-Cage Induction Motors – 500 Horsepower nad Larger,” Fifth Edition, American Petroleum Institute, Washington, D.C.

API 546, 2008, “Brushless Synchronous Machines – 500 kVA and Larger,” Third Edition, American Petroleum Institute, Washington, D.C.

API 684, 2005, "API Standard Paragraphs – Rotordynamic Tutorial: Lateral Critical Speeds, Unbalance Response, Stability, Train Torsionals and Rotor Balancing," Second Edition, American Petroleum Institute, Washington, D.C.

DIN 4024, 1988, "Machine Foundations – Flexible Structures that Support Machines with Rotating Elements," Deutsche Norm.

Finley, W. R., Hodowanec, M. M. and Holter, W. G. 2000, "An Analytical Approach to Solving Motor Vibration Problems," *IEEE Transactions on Industry Applications*, 36, pp. 1467-1480.

Fitzgerald, A. E., Kingsley, C., and Umans, S. D., 2003, *Electric Machinery*, Sixth Edition, New York: McGraw-Hill.

Holopainen, T. P., Roivainen, J., Waltzer, I. and Hellsten, J., 2010, "Support in Stator," *U.S. Patent 7,812,494*, Washington, DC.

Holopainen, T. P., Niiranen, J., Jörg, P. and Andreo, D., 2013, "Electric Motors and Drives in Torsional Vibration Analysis and Design," *Proceedings of the Fortieth Turbomachinery Symposium*, Turbomachinery Laboratory, Texas A&M University, College Station, Texas, 21 p.

Holopainen, T. P., 2015, "Prediction of ultimate coupling torque during transient short-circuit loads of electric motors," *Proceedings of the 9th IFToMM International Conference on Rotor Dynamics*, *Mechanics and Machine Science 21*. Cham, Switzerland: Springer International Publishing, pp 649-660.

IEC 60034-14, 2003, "Rotating Electrical Machines – Part 14: Mechanical Vibration of Certain Machines with Shaft Heights 56 mm and Higher – Measurement, Evaluation and Limits of Vibration Severity," Third Edition, International Electrotechnical Commission, Geneva, Switzerland.

IEC 60034-32 TS, 2015, "Rotating Electrical Machines – Part 32: Measurement of Stator End-Winding Vibration at Form-Wound Windings," Under Preparation in WG32, International Electrotechnical Commission, Geneva, Switzerland.

IEC 60287-1-1, 2006, "Electric Cables – Calculation of the Current Rating – Part 1-1: Current Rating Equations (100 % Load Factor) and Calculation of Losses – General," Second Edition, International Electrotechnical Commission, Geneva, Switzerland.

Owen, E. L., 1991, "Flexible Shaft Versus Rigid Shaft Electric Machines for Petroleum and Chemical Plants," *IEEE Transactions on Industry Applications*, 2, pp. 245-253.

Pyrhönen, J., Jokinen, T., and Hrabovcová, V., 2008, *Design of Rotating Electrical Machines*, Chichester, UK: John Wiley & Sons.

Tessarolo, A., Zocco, G., and Tonello, C., 2011, "Design and Testing of a 45-MW 100-Hz Quadruple-Star Synchronous Motor for a Liquefied Natural Gas Turbo Compressor Drive. IEEE Transactions on Industrial Applications," *47*, pp. 1210-1219.

